

Evidence Report:

Risk of Performance Decrement and Crew Illness Due to an Inadequate Food System

Human Research Program

Human Health Countermeasures Element

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I. PRD Risk Title: Risk of Performance Decrement and Crew Illness Due to an Inadequate Food System (AFT)

Description: Performance is critical for mission success. If the food system is not safe, nutritious, and acceptable, then crew health and performance and the overall mission may be adversely affected. The primary goal of the Advanced Food Technology Project (AFT) is to develop requirements, methods, and technologies that will enable NASA to provide an adequate food system characterized by the provision of safe, nutritious, and acceptable food to the crew. The requirements of the food system must be in balance with the requirements of all other systems and the available vehicle resources such as mass, volume, waste, and crew time. AFT is a project within the Human Health Countermeasures (HHC) Element with the Human Research Program (HRP) objective of developing capabilities and technologies in support of human space exploration, focusing on mitigating the highest risks to crew health and performance. Further details on HRP's AFT risk can be found at:

<https://humanresearchroadmap.nasa.gov/Risks/risk.aspx?i=87>.

II. Executive Summary of Evidence for Risk

NASA is preparing for long duration manned missions beyond low-Earth orbit that will be challenged in several ways, including long-term exposure to the space environment, impacts to crew physiological and psychological health, limited resources, and no resupply. The food system is one of the most significant daily factors that can be altered to improve human health, and performance during space exploration. Therefore, the paramount importance of determining the methods, technologies, and requirements to provide a safe, nutritious, and acceptable food system that promotes crew health and performance cannot be underestimated.

The processed and prepackaged food system is the main source of nutrition to the crew, therefore significant losses in nutrition, either through degradation of nutrients during processing and storage or inadequate food intake due to low acceptability, variety, or usability, may significantly compromise the crew's health and performance. Shelf life studies indicate that key nutrients and quality factors in many space foods degrade to concerning levels within three years, suggesting that food system will not meet the nutrition and acceptability requirements of a long duration mission beyond low-Earth orbit. Likewise, mass and volume evaluations indicate that the current food system is a significant resource burden. Alternative provisioning strategies, such as inclusion of bioregenerative foods, are challenged with resource requirements, and food safety and scarcity concerns. Ensuring provisioning of an adequate food system relies not only upon determining technologies, and requirements for nutrition, quality, and safety, but upon establishing a food system that will support nutritional adequacy, even with individual crew preference and self-selection. In short, the space food system is challenged to maintain safety, nutrition, and acceptability for all phases of an exploration mission within resource constraints.

This document presents the evidence for the Risk of Performance Decrement and Crew Illness Due to an Inadequate Food System and the gaps in relation to exploration, as identified by the NASA Human Research Program (HRP). The research reviewed here indicates strategies to establish methods, technologies, and requirements that increase food stability, support adequate nutrition, quality, and variety, enable supplementation with grow-pick-and-eat salad crops, ensure safety, and reduce resource use. Obtaining the evidence to establish an adequate food

system is essential, as the resources allocated to the food system may be defined based on the data relating nutritional stability and food quality requirements to crew performance and health.

III. Introduction

Throughout history, food and its limits have impacted the success or failure of human exploration and ambition. From 1500-1800, the lack of vitamin C in available rations resulted in rampant scurvy and the deaths of more sailors than all other causes combined (Pimentel 2003). During early polar exploration missions, attempts to reduce supply weight by caloric restriction and the dislike of available foods resulted in significant weight and muscle loss, malnutrition and psychological distress, which correlated with failed expeditions, and ultimately death (Pugh 1972).

During the Napoleonic wars more deaths were caused by malnutrition and food poisoning than combat (Featherstone 2012). Napoleon's need for a dependable food system led him to offer a reward that drove Nicolas Appert to develop the canning method (Featherstone 2012). Military and exploration continued to be a driving force for improvements in a dependable, shelf stable food system. The need to reduce mass in the twentieth century drove the advancement from solid cans to lightweight metallized pouches with superior product quality. Similarly, the need to ensure food safety through mission critical, medically limited situations drove the development of the Hazard Analysis Critical Control Point (HACCP) system by NASA, U.S. Army Natick Soldier Research, Development & Engineering Center (NSRDEC), and Pillsbury. HACCP has since improved food safety throughout food industry (Heidelbaugh 1966).

The evidence in this document indicates that requirements for exploration will need to drive further food system advancements to enable safe, productive, and successful Mars missions. Processing and prepackaging ensure a safe and nutritious food system for missions of several months, however, current processing and storage degrade nutrition and acceptability to a level that will not meet the requirements for a long duration mission. These challenges are further complicated by implications between food and psychology and resource constraints. The probability that the current food system will be inadequate increases with mission length and distance from Earth, where there will be no resupply.

Missions to an asteroid or Mars may be one to three years in length. The high mass and volume of a prepackaged food system may require the food to be shipped separately from the crew. Some scenarios require that the food be shipped in more efficient, but slower, propulsion systems that require a several year lead on the crew launch. This pre-positioned food may be three to five years old at the time of consumption. Currently, NASA's prepackaged foods have a stated shelf life of about two years, far short of the five-year minimum required for Mars missions. In addition, beyond low-Earth orbit, the food will be exposed to more severe sources of radiation, which have an unknown effect on the nutritional content and acceptability of the foods.

In order to provide a food system that supports crew health, performance, and well-being, extensive provisioning strategies must be evaluated. These strategies include incorporation of a bioregenerative system and novel processing and packaging scenarios that protect the food and reduce mass, volume, and waste. However, basic nutritional stability, continued acceptability, and safety only represent a fraction of the food system challenges for human space exploration. Of particular concern is the fact that the human state is altered in low-Earth orbit and pharmacological and medical interventions are extremely limited on long-duration missions.

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Instances of gastrointestinal distress (both diarrhea and constipation), increased stress and anxiety, symptoms of depression, potential increase in virulence of medically significant pathogenic bacteria, alterations in cytokine production and immune cell function, and alterations in microbial diversity have all been recorded on previous spaceflight missions, indicating the need for more effective countermeasures (Archibald and Kelleher 2015; Crucian et al. 2015a; Crucian et al. 2015b; Slack et al. 2015; Taylor et al. 1977; Wilson et al. 2007a). Further information related to key changes in human state in low Earth orbit are detailed in the HRP discipline evidence reports <https://humanresearchroadmap.nasa.gov/Evidence/>.

Food is a daily modifiable factor that has significant potential as a natural countermeasure to negative health outcomes. Increasing numbers of studies elucidate links between targeted dietary intake and all aspects of health (Boeing et al. 2012; Leenders et al. 2013; Macready et al. 2014). Whole fresh foods and a balanced diet provide all essential nutrients and thousands of bioactive compounds with synergistic benefits that cannot be replicated by a supplement (Liu 2003b). The body's microbiome utilizes compounds that are unavailable to human metabolism and converts them to metabolites that impact physiology and psychology via the gut-brain axis in ways that are only beginning to be understood (Cryan and Dinan 2012; Dethlefsen et al. 2007; Stilling et al. 2014; Wall et al. 2014). Additionally, the psychological importance of the acceptability, variety, and choice of food is evident in human exploration accounts. The adequacy of the food system becomes increasingly important in the harsh environments of isolation and confinement, where other comforts and familiarities are unavailable (Stuster 1996). Thus, an opportunity exists to define an exploration food system that not only supports nominal human health through stable basic nutrition, but acts as a natural countermeasure through defined functionality, stability, acceptability, variety and quality. This food system requires collaboration among the NASA HRP disciplines to target dietary interventions through implementable strategies.

The ability of a closed source, completely processed, and variety-limited food system to sustain nutrition and acceptability, while promoting human health and wellbeing for three years has never been demonstrated, and the ramifications are unknown. The research that AFT conducts focuses on gaps in the ability of the space program to provide an adequate food system for long duration missions. The following are gaps for this risk identified in the HRP Integrated Research Plan:

Food-01: We need to determine how processing and storage affect the nutritional content of the food system.

Food-02: We need to determine how the sensory and psychosocial acceptability of the food system changes due to microgravity, processing, storage, choice, and eating environment.

Food-03: We need to identify the methods, technologies, and requirements that will deliver a food system that provides adequate safety, nutrition, and acceptability for proposed long-duration Design Reference Mission operations.

Food-04: We need to identify tools or methods that can be used or developed to help mission planners and vehicle developers determine the most effective combination of methods, technologies, and requirements to balance crew food system needs with vehicle resources.

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The AFT research plan is only one part of the HRP research plan, and the evidence in this report is focused on food-specific solutions to provide a safe food system with stable nutrition and acceptable sensory attributes and variety for all mission scenarios. AFT is integrated with HRP disciplines such as Nutritional Biochemistry, Immunology, Microhost, and Behavioral Health, to determine appropriate food system designs and nutritional and caloric needs to meet unique performance expectations in exploration mission scenarios. This report only provides minimal human health and performance specific details as evidence for the need to determine technologies, requirements, and methods that enable provisioning of a stable and adequate food system. Further details on research into human health and performance impacts and their relationship to food and standard development may be found in other HRP discipline evidence reports: <https://humanresearchroadmap.nasa.gov/Evidence/>.

Specific cross-disciplinary factors include:

- Alterations in nutritional needs in spaceflight
- Impact of the food system on measures of physiology and performance in spaceflight
- Impact of the food system on human psychology in spaceflight
- Impact of food system requirements on vehicle design (i.e. food preparation and storage technologies, integration with water requirements and waste processing)

Current Space Food System:

In order to define an exploration food system, this report uses the current ISS food system as a baseline to define advantages and gaps in food safety, nutrition, and acceptability criteria and address concerns with vehicle resources. With the exception of Skylab, there has not been a refrigerator or freezer on board dedicated to food storage, due to resource constraints. Therefore, the food system has always been processed to inactivate microorganisms and enzymes and individually packaged to ensure food safety, stability, and ease of use in a medically and resource-limited microgravity environment.

The ISS food system, with minor fresh produce supplementation, is supported by resupply capabilities in low Earth orbit. The autonomy granted over food choice means that crewmembers do not eat prescribed diets on the ISS. However, the crew does not receive individual preference provisioning for the majority of their food supply. Due to resupply logistics, a standard food set rotates every 7-9 days, with variety balanced for nutritional needs as estimated by a nutrient database program. Crewmembers select their own meal choices from pantry-style containers packed by food type, which enables some selection for personal preferences, limited by how often containers can be opened and the preferences of crewmates. Crewmembers supplement this 7-9 day food set with personal preference food containers that may provide an additional 400-500 calories a day. Vitamin D is the only supplement provisioned with the food system for all crewmembers.

The different forms in which food has been provided to ISS include the following:

1. Thermostabilized - This process, also known as the retort process, heats food to a temperature that renders it free of pathogens, spoilage microorganisms and enzyme activity. Food items are placed into cans or metallized pouches and thermally processed with steam-

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overpressure or water-overpressure to remove excess air/oxygen for specified times and temperatures, resulting in commercially sterile food.

2. Irradiated - Irradiation is not typically used to process foods to commercial sterility. However, NASA has special dispensation from the Food and Drug Administration (FDA) to prepare nine irradiated meat items to commercial sterility (FDA 2011b). Irradiation involves the use of gamma rays, x rays, or electrons, and uses energy levels that assure negative induction of radioactivity in the irradiated product. It controls naturally occurring processes such as ripening or senescence of raw fruits and vegetables, and is effective for inactivation of spoilage and pathogenic microorganisms. Space flight foods are deep frozen in metallized pouches for processing.
3. Rehydratable - A number of technologies are available that allow for the drying of foods. Examples of these technologies are drying with heat, osmotic drying, and freeze drying. These processes reduce the water activity of foods, which results in the inability of microorganisms to thrive. Freeze drying is considered to produce a higher quality product and is used most commonly for space foods. Foods may have a shelf life of 18-24 months when vacuum sealed in metallized overwrap pouches.
4. Natural form - Natural form foods are commercially available, shelf-stable foods. The moisture of the foods may range from low moisture (such as almonds and peanuts) to intermediate moisture (such as brownies and dried fruit). These foods rely on reduced water activity in order to prevent microbial activity, and have a shelf life of 18 months when vacuum sealed in metallized pouches.
5. Extended shelf-life bread products - Items such as scones, waffles, and dinner rolls can be formulated and packaged to give them a shelf life up to 18 months when vacuum sealed in metallized pouches.
6. Fresh Food - Foods such as fresh fruit, vegetables, and tortillas that have a short shelf life are provided on a limited basis, more for psychological support than as a part of meeting dietary requirements. These foods are sourced from HACCP documented suppliers and disinfected following commercial chlorine wash protocols.
7. Beverages - The beverages currently used on the International Space Station (ISS) are either freeze dried beverage mixes (such as coffee or tea) or flavored drink powders (such as lemonade or orange drink). The drink mixes are prepared and vacuum sealed inside a metallized beverage pouch. In the case of coffee or tea, sugar or powdered cream can be added. Empty beverage pouches are also provided for drinking water.

The types of evidence provided in this document are labeled according to HRP's Categories of Evidence:

Evidence Category I: At least one randomized, controlled trial.

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Evidence Category II: At least one controlled study without randomization, including cohort, case-control, or subject operating as own control.

Evidence Category III: Non-experimental observations or comparative, correlation, and case or case-series studies.

Evidence Category IV: Expert committee reports or opinions of respected authorities based on clinical experiences, bench research, or “first principles.”

It is essential that an adequate food system include safety, acceptability, and nutrition within resource constraints for all aspects of exploration missions. These four factors - safety, acceptability, nutrition, and resource use - have several complexities that could be limiting if not designed correctly. Each factor is discussed separately in the following sections.

IV. Safety

A. Space Food Safety Background

Food safety is defined by the absence of a health risk due to physical, chemical and microbiological contamination. The recognition that microbiological contamination of food can negatively affect crew health, possibly compromise crew survival, and jeopardize mission success has driven food system design. Initial provisions must be shelf stable, meet microbiological requirements, and packaged to remain safe for the mission duration in a range of environmental conditions.

Microbiological safety is currently ensured through processing with the HACCP system, and Good Manufacturing Practices (GMPs). HACCP is a systematic and preventive approach to food safety that was developed by NASA, the United States Army Laboratory, and the Pillsbury Company in the 1960's. GMPs include employee qualifications and training, sanitation, recordkeeping, process validation, and facilities and equipment maintenance and verification (FDA 2011a).

The use of thermostabilization, irradiation, and drying (rehydratables) provides shelf stable foods and prevents a health risk from microbial contamination. After processing, the thermostabilized and irradiated food items are tested for pouch integrity and swelling to determine whether adequate heat was applied to the food to produce commercial sterility (Evidence Category IV). Safe production of rehydratable foods relies on preventative practices, such as the use of high quality ingredients, clean surfaces and safe-handling practices that prevent microbial contamination during processing. However, rehydratables and natural form foods are not commercially sterile and may still contain viable microorganisms that are prevented from growing by the low moisture content. Rehydratable foods and natural form foods are tested for viable microorganisms before flight to ensure microbiological standards are met. Additionally, crew are trained to discard food that they have not consumed within two hours of rehydration, as the conditions may allow microorganisms to grow.

Food microbiological safety is monitored by the Johnson Space Center's (JSC) Microbiology Laboratory to ensure that preparation and packaging procedures result in products

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that conform to established microbial standards for flight foods. Table 1 lists the items tested and the associated limits (NASA 2011).

Table 1. Microbiological Testing for Flight Food Production

Area/Item	Microorganism Tolerances	
Food Production Area	Samples Collected*	Limits
Surfaces	3 surfaces sampled per day	3 CFU/cm ² (Total aerobic count)
Packaging Film	Before use	
Food Processing Equipment	2 pieces sampled per day	
Air	1 sample of 320 liters	113 CFU/320 liters (Total aerobic count)
Food Product	Factor	Limits
Non-thermostabilized**	Total aerobic count	20,000 CFU/g for any single sample (or if any two samples from a lot exceed 10,000 CFU/g)
	Coliform	100 CFU/g for any single sample (or if any two samples from a lot exceed 10 CFU/g)
	Coagulase positive Staphylococci	100 CFU/g for any single sample (or if any two samples from a lot exceed 10 CFU/g)
	Salmonella	0 CFU/g for any single sample
	Yeasts and molds	1000 CFU/g for any single sample (or if any two samples from a lot exceed 100 CFU/g or if any two samples from a lot exceed 10 CFU/g <i>Aspergillus flavus</i>)
Commercially Sterile Products (thermostabilized and irradiated)	No sample submitted for microbiological analysis	100% inspection for package integrity

*Samples collected only on days that food facility is in operation

** Food samples that are considered “finished” product that require no additional repackaging are only tested for total aerobic counts

B. Evidence for Inadequate Food Safety During Spaceflight and from Ground-based Testing

Incidences of gastrointestinal distress have been recorded by crewmembers during missions, but none of these cases have been attributed to a foodborne illness (Crucian et al. 2015a; Hawkins and Zieglschmid 1975). Likewise, instances of spoiled food packages on orbit have been recorded once a year on average, but have not resulted in foodborne illness (Evidence

Category III). The crew is trained to identify bloated or spoiled packages and discard them, however passage of this inspection does not ensure that the food is safe.

There have been instances where rehydratable foods did not pass microbiological specifications due to contamination from mold, yeast, or bacterial pathogens detected during preflight testing. The JSC Microbiology Laboratory reported that 26 out of 1802 products failed to meet the microbiological specifications (Table 1) between 2012 to 2015 and hence were not approved for ISS flights. Though only a small number of the samples failed, even one contaminated food lot can result in crew illness and possibly death, especially given medical limitations as distance from Earth increases (Evidence Category I) (Archibald and Kelleher 2015). The use of HACCP, good manufacturing practices, standard operating procedures, and finished product testing of processed and prepackaged foods should prevent foodborne illness events during space missions, but the rare occurrence of spoiled food on ISS suggests that there is always a small risk of foodborne illness during flight.

C. Inadequate Food Safety in Context of Exploration Missions

There is no gap exclusively directed to food safety, as the current food processing and packaging procedures and microbiological testing protocols have demonstrated food safety capabilities that may meet the five year minimum requirements of a Mars missions, as long as the packaging is not compromised. Nutritional and acceptability gaps will require novel food system solutions. Food safety validation is a part of evaluating those solutions, which are included under mitigation gap Food-03, which simultaneously addresses nutrition and acceptability issues. The studies involving food safety validation are discussed following the introduction of nutrition and acceptability issues and gap Food-03, but are briefly introduced here.

Initial missions to Mars will most likely be supported by prepackaged foods. The potential for “pick-and-eat” salad crop supplementation is limited due to the extensive crew time and infrastructure requirements and risks associated with dependence on a bioregenerative food system. Safety issues for prepackaged foods increase for long-duration exploration missions. If prepackaged foods are prepositioned on the Mars surface, then the food packages may be compromised prior to the crews’ arrival. Packaging and storage evaluations are included in processing and shelf life studies that fall under Food-03.

The recent “Veggie” chamber experiment on ISS demonstrated the capability for a “pick-and-eat” salad crop system for spaceflight (Herridge 2015). If fresh fruits and vegetables are consumed without a heating (cooking) step, there is potential for microbial contamination, foodborne illness, and death, as demonstrated by the commercial produce-related *Escherichia coli* outbreaks in recent years (Aruscavage et al. 2006; Bielaszewska et al. 2011) (Evidence Category III). The methods to prevent produce contamination and the technologies to disinfect produce in spaceflight will be evaluated under gap Food-03. It is essential to identify sources of contamination during food production, processing, and preparation in a controlled closed-loop system, and determine safety procedures and testing methods to prevent possible foodborne illness. Mission loss or major impact to crew health would likely occur if food safety is not ensured.

It is expected that with initial successes of exploration missions, establishment of Mars bases, and proven bioregenerative capabilities, the percentage of the food system that is provided through bioregenerative methods will increase. Fresh food, bulk ingredients, processing and meal

preparation will provide the crew with more variety and the potential for improved quality and nutrition. However, food safety and availability will no longer be ensured, as current provisioning activities rely solely on ground-based processing, packaging, and microbial testing to ensure safety (Evidence Category IV).

Many foods must reach a certain time/temperature combination to ensure microbiological safety. If foods are processed during a mission consideration must be given to the changes in environment and the processing equipment and procedures that will be required to ensure safety on an extraterrestrial surface. Heat and mass transfer are affected by partial gravity and reduced atmospheric pressure. Additional safety measures may be required for dry ingredients, based on recent Salmonella outbreaks related to low moisture foods (Finn et al. 2013). Novel methods and technologies related to food safety will be evaluated under gap Food-03.

The majority of the human spaceflight work has been centered on prevention of pathogens and foodborne illness. However increasing numbers of studies indicate the importance of the symbiotic relationship between humans and microorganisms that are naturally acquired from both the food system and the environment. Such relationships are essential to immune and psychological homeostasis (Cryan and Dinan 2012; Dethlefsen et al. 2007; Wall et al. 2014). While the spaceflight food system is fully processed and shelf stable, the introduction of generally recognized as safe (GRAS) probiotic microbes has the potential for use as a safe, non-invasive, daily countermeasure to immune dysregulation and physiological and psychological alterations (Akkasheh et al. 2016; O'Flaherty and Klaenhammer 2010; Turrone et al. 2014; Urbaniak and Reid 2016) (Evidence Category I).

The incorporation of probiotics will require protocols to ensure pure bacteria cultures are safely added and meet shelf life requirements (Cooper et al. 2011b). Several studies indicate the potential for inclusion of probiotics in spaceflight. The studies fall under gap Food-03, but will be discussed here. One study demonstrated that provisioning probiotics in a rehydratable dairy (or similar) food matrix within the space food system is more adequate than a capsule in delivering stable and consistent amounts of probiotics through gastrointestinal transit. However, refrigeration or freezing capabilities would be required to ensure shelf stability for multi-year missions (Douglas et al. 2014). Another study indicated that the characteristics of the probiotic strain *Lactobacillus acidophilus* ATCC 4356 would translate to the spaceflight environment, and therefore Earth-based benefits could be expected (Castro-Wallace et al. 2015). Further investigations into the effects of probiotic strains on human health and immunity during spaceflight would elucidate their potential as a countermeasure on long duration missions.

V. Nutrition

A. Space Food Nutrition Background

Adequate nutrition has two components – 1) necessary nutrients and 2) caloric energy (protein, carbohydrate, and fat). It is possible to consume sufficient calories without adequate nutritional intake, resulting in deficiency diseases that diminish health, impact performance and in extreme cases lead to loss of life. It is also possible to provide excessive amounts of nutrients resulting in or contributing to adverse health conditions. It is essential that the crewmembers are provided with the required level of each nutrient throughout their missions. Table 2 summarizes the nutritional requirements for spaceflight (NASA 2011).

Table 2. Nutrition Composition Breakdown

Nutrients	Daily Dietary Intake
Protein	0.8 g/kg And $\leq 35\%$ of the total daily energy intake And 2/3 of the amount in the form of animal protein and 1/3 in the form of vegetable protein
Carbohydrate	50-55% of the total daily energy intake
Fat	25-35% of the total daily energy intake
Ω -6 Fatty Acids	14 g
Ω -3 Fatty Acids	1.1 - 1.6 g
Saturated fat	$<7\%$ of total calories
Trans fatty acids	$<1\%$ of total calories
Cholesterol	< 300 mg/day
Fiber	10-14 grams/4187 kJ
Fluid	≥ 2000 mL
Vitamin A	700-900 μ g
Vitamin D	25 μ g
Vitamin K	Women: 90 μ g Men: 120 μ g
Vitamin E	15 mg
Vitamin C	90 mg
Vitamin B12	2.4 μ g
Vitamin B6	1.7 mg
Thiamin	Women: 1.1 μ mol Men: 1.2 μ mol
Riboflavin	1.3 mg
Folate	400 μ g
Niacin	16 mg NE
Biotin	30 μ g
Pantothenic Acid	30 mg
Calcium	1200 - 2000 mg
Phosphorus	700 mg And ≤ 1.5 x calcium intake
Magnesium	Women: 320 mg Men: 420 mg And ≤ 350 mg from supplements only
Sodium	1500 - 2300 mg
Potassium	4.7 g
Iron	8 - 10 mg
Copper	0.5 - 9 mg
Manganese	Women: 1.8 mg Men: 2.3 mg
Fluoride	Women: 3 mg Men: 4 mg
Zinc	11 mg

Nutrients	Daily Dietary Intake
Selenium	55 - 400 µg
Iodine	150 µg
Chromium	35 µg

B. Evidence of Inadequate Nutritional Content of Food and Intake During Spaceflight

The importance of nutrition in the adaptation of astronauts to weightlessness has been recognized since the Gemini program (Rambaut et al. 1975). Nutritional data from past missions indicate the health risk of inadequate caloric and nutrient intake, especially as mission length increases. Crewmembers often experienced reduced appetite, possibly due to a combination of effects such as fluid shifts, pressure changes, nausea, and work load (Rambaut et al. 1975; Smith et al. 2005). Reports show that the average caloric intake during the Mercury, Gemini, and Apollo missions was about 1,880 +/- 415 kcal/day. This value was consistently lower than quantities necessary to maintain body weight (about 2,870 kcal/ day), resulting in body mass losses during all missions (Smith et al. 1975). The inadequacy of specific nutrients in the Apollo diet compounded the issues from insufficient caloric intake. Apollo food provided only marginal amounts of nicotinate, pantothenate, thiamine, and folic acid (Rambaut et al. 1975). The occurrence of arrhythmias in Apollo 15 astronauts was attributed to a potassium deficiency in the space food system (Smith et al. 1975). The potassium deficiency in this short-term mission was mitigated in later missions through potassium supplementation (Evidence Category III).

Longer term effects of space travel on nutritional profiles of astronauts have been documented through physiological changes during the three to six-month long Mir and ISS Expeditions (Smith et al. 1999; Smith et al. 2005). Body mass and nutrient contents in urine, blood, plasma, and serum were measured post-flight in some ISS crew members and statistically compared to preflight baselines. Of particular concern were the decreased levels of several vitamins and minerals in the urine, blood, plasma, and serum. For example, Vitamin D levels, antioxidant capacity, γ -tocopherol levels, and folate levels were all significantly lower post-flight, which generated concern over the possibility of malnutrition during ISS Expeditions. The reduced caloric intake on ISS Expeditions (around 80% of recommended intake during space flight), as documented in 2005, led to an average weight decrease of 5%, potentially explaining some of the measured nutrient decreases (Smith et al. 2005). Body mass losses in some ISS and Mir crewmembers have been measured as high as 10-15% (Lane et al. 2007; Smith et al. 1999; Smith et al. 2009). (Evidence Category II)

The recorded body mass losses are particularly concerning considering that a study on hunger strikers estimated that body mass losses around 30% resulted in death (Leiter and Marliss 1982). It has been suggested that the inadequate nutritional profiles of astronauts in most space missions confound all other medical data interpretation (Smith et al. 2009). The Skylab crews, who were required to eat enough to meet their caloric needs, preserved body mass (Thornton and Ord 1975).

Prior to 2008, foods were provisioned for ISS based on crew preference. However, unlike Shuttle missions that launched the food with the crew, the ISS food supply was affected by delays in resupply missions. Shifts in arrival of a crew's chosen foods and potential shifts in preference over time may have increased dietary dissatisfaction, leading to subsequent reductions in consumption and body mass loss in some crewmembers. In 2008 the previously described

standard menu was implemented on ISS to provide variety despite resupply delays. The importance of diet was demonstrated over the next few years, as crew who maintained vitamin D status, consumed adequate calories to maintain body mass, and used the Advanced Resistive Exercise Device (ARED) were able to maintain bone mineral density through their mission (Smith et al. 2012). More information on inadequate nutrition can be found in the Evidence Report for the Risk Factor of Inadequate Nutrition (Smith et al. 2009).

Adequate nutrition also presupposes that harmful excesses of certain nutrients are not provided by the standard diet. To prevent high sodium concentrations from exacerbating bone loss and potential intracranial pressure-related vision changes in microgravity, the ISS food system was reformulated to reduce the average daily sodium intake from 5300mg/day to 3000 mg/day (Lane et al. 2013). High iron intake in spaceflight has been linked to increased serum ferritin and subsequent biomarkers of oxidative stress in ISS crew members (Zwart et al. 2013). Though the recommended daily intake of iron is 8-10 mg/day, the average intake aboard ISS is 20 ± 6 mg/day and is individually estimated to be as high as 47 mg/day for particular crew members on some days during the mission.

C. Inadequate Nutritional Content of Food and Intake in Context of Exploration Missions

Crews on long duration missions may only have access to foods that have been stored for five years at room temperature by the end of their mission. Preliminary studies indicate that current space food technology is not adequate to maintain the nutritional content of the food for five years. Inadequate delivery of a single nutrient or insufficient caloric intake may result in diminished physiological attributes and cognitive function, including weight loss, proteinuria, and hematuria (Friedl and Hoyt 1997) and the potential for depression, mood impairment, and increased aggression (Logan 2004; Singh 2014), which may limit the crew's ability to complete mission critical tasks. Furthermore, extended periods of malnutrition could result in crew illness and possibly death. Inadequate stability and availability of health-promoting fruits and vegetables, phytochemicals, and omega-3 fatty acids may reduce the status of multiple aspects of health and influence progression of chronic diseases on long duration missions (Boeing et al. 2012; Leenders et al. 2013; Macready et al. 2014; O'Keefe et al. 2015; Wall et al. 2010). Inadequate nutritional content of the food could delay a long duration mission beyond low-Earth orbit even if all other mission elements are ready.

D. Evidence of Inadequate Nutritional Content of Food and Intake for Exploration Missions – Ground and Spaceflight Research

Food loses nutrients through processing and during storage, and may not have the expected nutritional content when consumed. Nutrient changes during processing and throughout shelf life include isomerization of vitamins or vitamin precursors, changes in bioavailability of amino acids and vitamins as the food structure is broken down, and nutrient degradation, including oxidation of several vitamins and amino acids (Chen et al. 1995; Dewanto et al. 2002; Graziani et al. 2003; Gregory 1996; Rock et al. 1998; Seybold et al. 2004). Changes in vitamin content of certain processed foods stored at various temperatures for two years demonstrates the potential for significant degradation (Kamman et al. 1981; Kim et al. 2000; Kramer 1974; Lund 1975; Pachapurkar and Bell 2005). Canned fruits and vegetables stored for

two years at 27°C showed losses in ascorbic acid, riboflavin, and thiamin as high as 58%, while the same products held at 10°C only showed maximum losses of 38% (Cameron et al. 1955) (Evidence Category I). Currently, the commercial food industry does not require foods to extend beyond two years (Evidence Category III), so little research exists past this point.

The ability of the food to meet the nutritional requirements and its potential for use during long duration missions can only be determined if the nutritional profile of the entire space food system is known at the time of consumption. Until recently, there was limited empirical nutritional data for flight foods. Macronutrients and some minerals were determined chemically at the JSC Water and Food Analytical Laboratory (WAFAL) but many micronutrients were only calculated with a computerized nutrient database (Genesis R&D) developed by the USDA and the food industry, which does not provide an estimate of nutrient degradation due to specific processing, formulation, and packaging characteristics, or due to storage time and spaceflight conditions. In the absence of empirical nutrient data specific to the space food system, it is unknown whether the processing, storage, and environmental effects are accurately reflected in the computerized nutrient database, or whether these processed foods would be nutritionally adequate if consumed after five years of storage.

Radiation levels expected during deep space missions may contribute to nutrient and quality losses and exploration vehicles will be limited in available mass or power to provide cold storage for food. Food-specific nutritional stability may also impact nutritional adequacy over time, and vary with individual crewmember food choice over extended mission durations. Therefore, it is critical to accurately measure the degradation rate of nutrients in each flight food over the required shelf life, as well as identify foods where degradation is a concern and determine mitigation strategies in order to prevent deficiencies on these missions.

Many of the studies reviewed here involve evaluation of the product through processing and shelf life. Changes in food, whether nutritional or quality, occur through chemical reactions. All chemical reactions in food adhere to the simple general rate equation of

$$-\frac{d[A]}{dT} = k[A]^n$$

where A is the quality attribute being measured, T is the time, k is the rate constant, and n is the reaction order (Labuza and Schmidl 1985). Reaction rates are calculated after testing confirms which chemical reaction in a food will determine the ultimate shelf life endpoint. These reactions can serve as models to theoretically determine shelf life in similar foods.

Most quality reactions in food are zero or first order. Zero order reactions have a constant change in quality over time. Typical zero order reactions ($n = 0$) are enzymatic browning, non-enzymatic browning, and lipid oxidation. Typical first order reactions ($n = 1$) are protein and most vitamin deterioration, and microbial growth. Although not many reactions in food are second order ($n = 2$), it has been reported that in limited oxygen, the degradation of Vitamin C is second order (Labuza 1982).

The Q_{10} is a measure of how the rate changes for every 10°C change in temperature. Q_{10} is defined as

$$Q_{10} = \frac{\text{Shelf life at temperature } T^{\circ}\text{C}}{\text{Shelf life at temperature } (T^{\circ}\text{C} + 10)}$$

If a reaction that changes the product color happens in half the time at 10°C higher temperature, then the $Q_{10} = 2$ (Perchonok 2002).

Since food is not a model system, it is not simple to estimate Q_{10} ; however, typical Q_{10} values are shown in Table 3. Table 3 also shows that there is no definitive Q_{10} for a given category of food and that each type must be tested to determine its own Q_{10} . A food may have several Q_{10} values, each contributed by different reactions, such as lipid oxidation and Maillard browning (Perchonok 2002).

With Q_{10} values calculated, product shelf life can be projected using the formula:

$$t_s = t_0 e^{-aT}$$

where:

t_s = shelf life desired

t_0 = shelf at a reference temperature

a = slope of the line equal to $\ln Q_{10}/10$

T = temperature difference between temperature at which the shelf life, t_s , is desired and the reference temperature

Table 3. Q_{10} values for various food preservation methods

Food Preservation Method	Q_{10}
Thermally Processed	1 – 4
Dehydrated	2 – 10
Frozen	3 – 40

Shelf life information may be collected at a faster rate using accelerated shelf-life testing (ASLT) and the Q_{10} value. ASLT requires three storage temperatures 1) a control temperature where no changes are expected to occur through shelf life, 2) the expected storage temperature, and 3) an elevated temperature to accelerate reactions rates. The reaction rates and resulting shelf life at the elevated temperature can be used to determine the shelf life at the current temperature using the Q_{10} value (Perchonok 2002). However, the elevated temperature may cause changes that would not normally occur in foods at regular storage temperature, such as melting, protein denaturation, and increased water activity (Labuza and Schmidl 1985). These changes must be considered when analyzing shelf-life data.

The complexities of food structure and variety of components make food a dynamic system, which increases the difficulty in quantifying changes with kinetic models. The loss of vitamins to leaching, whether the vitamins are consumed in the leach liquid, the loss of nutrients during thermal processing, and the potential for increases in nutrient bioavailability as the food matrix is broken down during processing create an ambiguous picture of the actual nutritional content of processed foods. While the literature attempts to quantify the changes in nutritional content, the answers are not always obvious.

Kinetic data have previously been determined for the loss of several nutrients under pre-determined processing and storage conditions, but the rate constants provided are specific to the food and the testing parameters (Evans et al. 1981; Feliciotti and Esselen 1957; Kamman et al. 1981; Kirk et al. 1977; Lathrop and Leung 1980; Mulley et al. 1975; Rao et al. 1981) (Evidence Category I). Hence, despite significant kinetics data on thiamin, riboflavin, vitamin C, vitamin A, vitamin B6, and folic acid, the potential application for flight foods is limited due to differences in processing, packaging, and potential long duration mission storage temperature

range. As an alternative to extended food system or model system experimentation, it has been suggested that two isothermal or nonisothermal endpoints can be used in conjunction with modelling software to predict any other degradation point (Peleg and Normand 2015; Peleg et al. 2016). The model has yet to be verified with the space food system and likely would contain the previously published errors in estimation found with other food systems of up to 15%. However, versatile kinetic models that require limited experimental inputs are a promising method to inform the food nutrition risk given current NASA funding limitations that do not support statistically significant evaluation of the nutritional kinetics and stability in all space food products.

Nutritional delivery is further complicated by nutrient bioavailability from each food matrix. The concentration of nutrients in combination with the bioavailability of the nutrients determines the degree of nutrient delivery to the crewmember. Supplemental forms of vitamins and minerals generally are better absorbed by the body than the natural forms of the micronutrient, though this phenomena is not true for vitamin E and riboflavin (Golbach et al. 2014; Lodge 2005; Nelson et al. 1975; van het Hof et al. 2000). Competitive absorption and inhibiting and promotional interactions between compounds also impact nutrient absorption. Beta-carotene competes with other carotenoids for intestinal absorption (Tyssandier et al. 2002; van het Hof et al. 2000). Likewise, zinc limits iron absorption when the two are consumed simultaneously. Phytate and phytic acid, naturally occurring compounds in plants, inhibit the mineral absorption of calcium, chromium, iron, magnesium, phosphorus, and zinc (Gibson et al. 2006; Harland 1989). Some vitamins, such as vitamins A and E, have increased bioavailability if some fat is consumed simultaneously (Hedren et al. 2002). Vitamin A, riboflavin, and vitamin C show increased absorption if more dietary fiber is present at consumption so that the vitamins have a longer gastrointestinal residence time for absorption (Leonard et al. 2004) (Evidence Category I). The vitamin form and surrounding matrix along with the other dietary choices consumed simultaneously ultimately affect whether adequate nutrition is available from the food system.

In addition to the nutritional risks from nutrient degradation and gaps in nutrient kinetic knowledge, space missions will have a unique nutritional risk associated with extensive extravehicular activities (EVA) and emergency contingency requiring extended crew time in pressurized suits (over 100 hours). EVAs will require no less than an additional 200 kilocalories above nominal metabolic intake, similar in nutrient composition to the rest of the diet, per EVA hour (NASA 2011) (Evidence Category II). Currently, there is no effective delivery method for providing nutrition to the crew during extended time in a pressurized suit. This would be especially concerning over a multiple day event in which crewmembers are expected to be cognitively functioning and physically capable of performing tasks required for safe return. The insufficient nutritional delivery capabilities and lack of accurate nutrient data create the knowledge gap for this risk, Food-01.

Food-01: We need to determine how processing and storage affect the nutritional content of the food system.

Several projects have analyzed the adequacy of the nutritional availability in some spaceflight foods (Cooper et al. 2011a). Most recently, 24 vitamins and minerals were measured in 109 NASA food items at one month, one year, and three years post-processing (Cooper 2016). The foods in this study were processed according to current space food production protocols and

then stored at 21°C for up to three years. Four nutrients were found to be below the concentrations required to meet recommended daily intake for the crew at production, even with dietary compliance to the standard spaceflight food menu. Vitamin D has generally low levels in food. The deficit of vitamin D, due largely to lack of exposure to sunlight, has always been mitigated with a supplement on ISS. Both potassium and calcium concentrations in the space food system were approximately 20% lower than recommended intake levels. Finally, the space food system had a projected 13% daily nutrient shortfall of vitamin K (Evidence Category III).

Processing was shown to have some impact on the nutrient content of space food (Cooper 2016). Pre-processing estimates compared to post-processing empirical measurements suggest that vitamin B₆ and niacin concentrations decreased following irradiation with the exception of niacin in poultry, which increased. Vitamin D was also shown to increase in mushrooms following irradiation. Vitamin A degradation of 22% – 85% from original levels was also noted after irradiation. Food analysis after thermostabilization showed vitamin C, A, B₆, B₁₂, folic acid, and thiamin concentrations declined in specific space foods. Food analysis after freeze drying showed decreases as high as 84% in vitamin C, B₆, B₁₂, niacin, and thiamin in select food items but stability in other foods. (Evidence Category III).

Assessment of the 109 spaceflight foods through three years has indicated that vitamin C and thiamin are two vitamins with concerning trends (Cooper 2016). Therefore, a study is underway to provide kinetic modeling data for vitamin C and thiamin in space food system applicable processing and storage conditions to inform approaches that will enable their stability throughout the food system (Xiao et al. 2015).

Ground-based studies have provided the bulk of nutrient degradation data for spaceflight foods, but it is critical to understand how the space environment will impact nutrition over storage. To date, nutritional profiles have only been measured for five food items exposed to low Earth orbit (Evidence Category I). These foods received a cumulative radiation dose of 74.53 mGy over 880 days on ISS, which did not cause a significant decrease in the 30 nutrients measured. However, folic acid, thiamin, and Vitamins K and C decreased and lipid peroxidation increased over the 880 days in orbit similarly to samples stored on Earth (Zwart et al. 2009), providing further evidence for the loss of nutrients from the space food system over long duration storage.

While radiation in low Earth orbit did not compromise the nutrition in this limited test sample, the effects of continual exposure to mixed types of radiation in deep space are unknown (Zwart et al. 2009). In the case of a bioregenerative food system, radiation may affect the plants' ability to germinate and grow or affect resulting functionality in the absence of sufficient protection (Wilson et al. 2007b). It is important to determine if mitigation strategies, such as cold storage or the addition of antioxidants to the food (Gandolph et al. 2007; Wilson et al. 2007b) will be required to prevent nutritional deficiency that may compromise a mission. Earth-based radiation facilities could provide an indication of radiation effects in deep space, however they are limited in spectrum capability. Given the different effects that even gamma and electron beam have on nutrition (Group 1999), a full spectrum evaluation is needed to determine the risk of nutritional loss. As spaceflight missions extend beyond the Van Allen belt in the next decade it is expected that there will be opportunities to store food in deep space for evaluation over time.

The second gap that applies to nutrition is Food-03, which is a mitigation gap that simultaneously addresses solution to issues with nutrition, acceptability, and safety, and therefore will be discussed following the introduction of the acceptability gap.

VI. Acceptability

A. Space Flight Acceptability Background

Food acceptability can be defined and determined in several ways. Commercially, food acceptability is equated to sensory acceptability and includes appearance, flavor, texture, aroma, and serving temperature. Flight foods are evaluated for sensory acceptability by a panel of 30 or more untrained consumers. The sensory attributes of the products are rated using a 9.0-point Hedonic Scale, where 9 is the highest acceptability score (Chambers and Wolf 1996). Food products must receive an overall score of 6.0 or higher to be included in the space food system. Similarly, prior to each mission, crewmembers evaluate all menu items and those with the highest acceptability score are recommended for their crew specific containers.

Food system variety and usability are also factors used in defining acceptability. A large variety of food is needed to provide the crew choices and to avoid menu fatigue. The monotony effects from repeated food exposures are factors of duration of exposure, the initial pleasantness of the foods consumed repeatedly over time, and frequency and recency of eating the food (Hetherington et al. 2002). The familiarity and variety that supports individual crewmember preference must be provided, especially when considering that food is consistently identified in ISS debriefs as one of, if not the most, important factor to crew morale. The variety and quality are important to motivate consistent caloric intake and prevent nutritional deficiency and weight loss. If the food is difficult to prepare or eat, then the overall acceptability, and potentially consumption, of the food is reduced (Smith et al. 1975). The consumer can have their mood altered by food, and the mood can in turn drive decisions about food (Hussin et al. 2013; Singh 2014; Zellner et al. 2006). Finally, food acceptability can be affected by the social context and timing of meals. Food and mealtimes can play a primary role in psychological-social benefits by promoting unity and reducing the stress and boredom of prolonged space missions.

B. Evidence of Inadequate Acceptability During Spaceflight

The acceptability of the food system has been linked to caloric intake and associated nutritional benefits. If the food is not acceptable to the crew, then the crew will not eat an adequate amount and will be compromised nutritionally. Large improvements and advances in the space food system were achieved during the Apollo food program with the addition of thermostabilized and irradiated foods (Perchonok and Bourland 2002). Nevertheless, the majority of Apollo astronauts did not consume sufficient nutrients and experienced loss of body weight, fluids, and electrolytes (Smith et al. 1975).

A historical database reviewing the Apollo experience was generated based on 14 surviving Apollo astronauts' responses to 285 questions (Scheuring et al. 2007). The identification of medical issues during Apollo 7 through 17 provided evidence to modify medical requirements for future exploration missions (Scheuring et al. 2007). The astronauts answered 28 questions in 11 categories relating to food and nutrition, providing 76 responses and eight recommendations. It was reported that reduced food consumption may be partially attributed to a combination of physiological effects such as fluid shifts, pressure changes, nausea, issues preparing food, issues with the water system, and work load, but acceptability and familiarity of the food were also critical to consumption (Rambaut et al. 1975; Scheuring et al. 2007). Changes

in the sensory perception of the food were noted between ground-based taste tests and Apollo and Shuttle missions, indicating a potential effect of fluid shifts on sensory perception. Apollo crewmembers have also stated that the cabin temperature was cold and having hot water for hot drinks was important, and provided a psychological boost (for example, having coffee in the morning) (Scheuring et al. 2007). (Evidence Category III)

Consistently during ISS crew debriefs, the crews have stated that their food preferences change from preflight to flight (documents not published due to confidentiality). Similar to Apollo and Shuttle, the crews have also noted that their tastes for certain foods change in microgravity and they may crave different foods on orbit compared to on Earth. Similar statements were even made on Skylab, the only missions to date with frozen and refrigerated food. Joseph Kerwin commented about the Skylab eating experience by saying “the food seemed to have less taste in orbit than on the ground. NASA devised some tests to assess that on the second and third flights; the results were inconclusive; I think it was just the relative monotony of the diet and the urge for a little variety (Kerwin and Seddon 2002).” (Evidence Category III)

ISS crews have noted in crew debriefs that they would prefer more food variety for the length of the missions and they tire of certain foods over six months. Since the diets of the crewmembers during a mission are limited to just those items available, the long-term acceptability of some items may decrease with menu fatigue.

Currently, food resupply on ISS is dependent on allotment of cargo space and crew size predictions. Food stowage may not be allotted on every resupply vehicle so food may be sent into orbit months in advance of a crew’s arrival. Reductions in crew size have resulted in extra food on orbit that must be consumed. This results in consumption of some foods after three years of storage, which decreases acceptability and intake. Some ISS crews have consumed some foods three years post-processing, necessitated by resupply schedules and changes in crew size. Crewmembers have reported that these foods have decreased in acceptability, some to the point where they are no longer consumed (Evidence Category III).

C. Inadequate Acceptability of Food in Context of Exploration Missions

Crews on long duration missions may only have access to foods that have been stored for five years towards the end of their mission. Current space food technology is not adequate to maintain food acceptability for five year missions. Inadequate food acceptability decreases food consumption and may affect crew nutrition and psychosocial health, and limit the crew’s ability to complete mission-critical tasks (Friedl and Hoyt 1997).

Crew on long duration missions will likely have international cultural backgrounds that impact their food expectations. During the Russian Mars 500 study, the food system met energy and macronutrient requirements, but did not agree with the cultural eating habits of some crew members, leading to psychological discomfort and open complaints. The autonomy of the crew and the impossibility of provisioning resupply sustained an unacceptable food situation that caused a significant level of psychological discomfort. When a more international diet was provided after the simulated Mars landing, the psychophysiological state of the crew improved (Ushakov et al. 2014). (Evidence Category I).

Limited variety within food categories on long duration missions may have potential health consequences. It has been shown that a diet with high botanical diversity, which included fruits and vegetables from 18 botanical families, was more effective than an equal diet of just five botanical families to induce a reduction in oxidative damage of lipids or DNA (Thompson et

al. 2005). The botanical diversity of the diet likely impacts the bioactivity of dietary chemicals and the smaller amounts of many phytochemicals may have greater potential to exert beneficial effects than larger amounts of fewer phytochemicals. Diet diversity has also been linked to lower incidences of gastric cancer, brain health, psychological function, and gut microbiome (Foster and McVey Neufeld 2013; Heiman and Greenway 2016; Shiraseb et al. 2016; Vecchia et al. 1997). Impacts from inadequate diversity could be amplified by self-imposed limitations of individual crewmember choice within the available variety and inability to support preference changes over time.

Inadequate quality, variety, or usability of the food system could delay a long duration mission beyond low-Earth orbit even if all other mission elements are ready.

D. Evidence of Inadequate Acceptability of Food for Exploration Missions – Ground and Spaceflight Research

Sensory acceptability can be affected by factors such as serving temperature, product age and formulation, storage environment, variety, and place of consumption. Food quality (color, texture, etc.) may also provide a general indication of nutritional loss of the food (Lund 1988). There are two gaps contributing to this risk. The first gap is a knowledge gap, and focuses on all aspects of defining an acceptable food system (Food-02). The second gap is a mitigation gap and simultaneously investigates solutions to nutrition, acceptability, and safety issues (Food-03).

Food-02: We need to determine how the sensory and psychosocial acceptability of the food system changes due to microgravity, processing, storage, choice, and eating environment.

A familiar and acceptable food system will be important to both physical and psychological well-being during long duration missions. Previous studies have shown that decreased acceptability reduces food consumption and leads to weight loss and deterioration of health (Friedl and Hoyt 1997). The food quality, variety, environment, and social setting surrounding eating experiences were all shown to influence unity and morale in extraterrestrial analog Antarctic expeditions (Hunter et al. 2003; Leon et al. 2000). Shared food preparation and food familiarity have been found to be important to relieve anxiety and promote bonding (Locher et al. 2005). In previous diabetes menu studies, results indicate that even within controlled food system environments, greater food variety and more control over food selection results in greater satisfaction with the food system overall (Curll et al. 2010). Lack of food choice and limited variety may result in food fatigue and aversion to specific foods for some subjects in as little as 30 days (Caldwell et al. 2014). Studies conducted by the armed forces in the 1950's showed that most foods decreased in acceptability when repeatedly consumed. The degree of loss of acceptability depended on the specific food (Vickers 1999) (Evidence Category III). Information on changing food preferences over time can inform food system variety design through a long duration mission.

Previous work evaluated nutritional and acceptability changes in 13 representative thermostabilized spaceflight foods, using accelerated shelf life testing to assess the potential of the current food system for use during long duration missions. The sensory, quality, and nutrition of each product was determined at regular intervals over three years of storage at 4°C (control), 22°C (storage temperature of actual flight food), and 35°C (accelerated temperature) (Catauro and Perchonok 2012) (Evidence Category I). Egg products were not compatible with

the thermostabilization process, and were unsuitable immediately after production. There were considerable losses in folic acid and B and C vitamins, often correlating with unacceptable changes in flavor or color. Other vitamins appeared to be maintained throughout shelf life. Low temperature storage (4°C) maintained product quality throughout the study. The changes in quality and nutrition were used to determine the shelf life of each item (Catauro and Perchonok 2012).

The shelf life values were extrapolated to NASA’s 65 thermostabilized items (Figure 1). Meat products and other entrées were projected to maintain sensory quality the longest, over three years, without refrigeration. Fruit products and dessert products followed with 1.5-5 years, then starches and vegetable side dishes with one to four years. Approximately 10% of the 65 thermostabilized items are estimated to have a shelf life of five years or more and 45% of the products are estimated to have a shelf life of more than three years. In general, the major determinants of shelf life appear to be the development of off-flavor and off-color over time. Analysis of these 13 thermostabilized products suggests that new processing and storage technologies must be investigated in order to improve initial quality and extend shelf life of food products for use in long-duration missions⁸² (Evidence Category I).

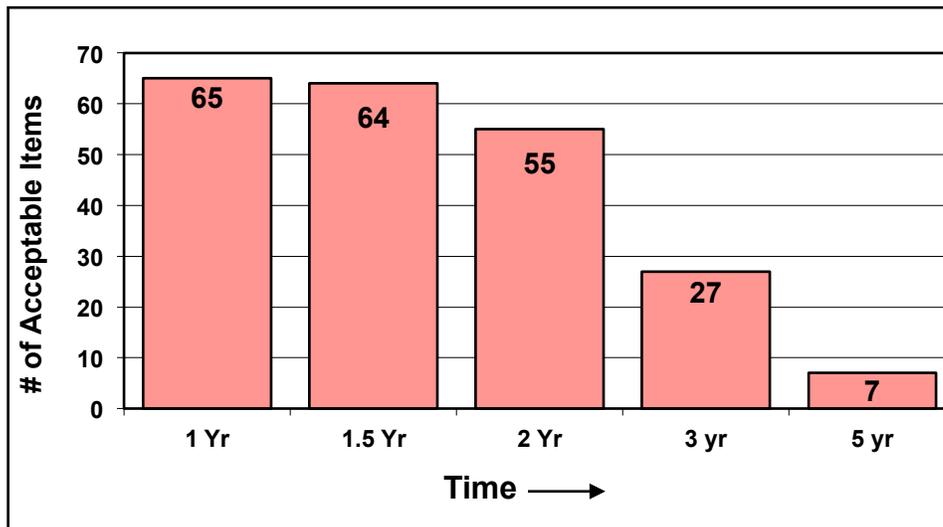


Figure 1: Number of acceptable thermostabilized space foods decreases by 90% over five year shelf life.

Inadequate acceptability of the space food systems for next generation NASA and commercial space vehicle concepts is likely caused by resource constraints on these vehicles, which have led to the elimination of a food warmer or hot water on some planned missions. A study conducted at JSC’s Space Food Systems Laboratory in 2006 measured the acceptability of ambient temperature food that would normally be consumed hot. The study showed that the food lost about 20% of its acceptability when consumed at room temperature and about 17% of the food items were determined to be unacceptable (unpublished data, Evidence Category I).

Reduced overall initial sensory acceptability, due to individualized alterations in sensory perception of foods as experienced by some astronauts and cosmonauts in microgravity, is particularly concerning (Evidence Category III). The contradictory results obtained from in-flight and analog studies investigating flavor alterations were likely complicated by unknown contributions from physiological and psychological stresses experienced during spaceflight,

including nasal congestion, bodily fluid redistribution, space adaptation sickness, and isolation (Olabi et al. 2002). Insufficient food acceptability contributed to inadequate caloric and nutritional intake in past missions, and will be more detrimental as mission length and distance from Earth increases.

Complete autonomy in menu selection is an important component of menu acceptability, however, this practice may decrease nutritional delivery in aged space food. Exclusion diets using the standard ISS menu would not allow adequate delivery of micronutrients after three years of storage. When breads and cereals are excluded from the space food diet (by plan or crew selection), the delivery of folic acid is likely to fall to 86% of the recommended daily intake; exclusion of fortified drinks also adds considerable limits to vitamin C delivery. When vegetables are excluded from the space food diet (by plan or crew selection), the delivery of vitamin K falls to a paltry 37% of the recommended daily intake of the vitamin (Cooper 2016).

The effects that changes in sensory perception, menu fatigue and preference changes, variety, and personal control have on appetite, acceptability, and crew mood over long durations still needs to be investigated. Insight into the factors contributing to reduced sensory acceptability and food consumption would enable effective countermeasures to be implemented. Specifically, relationships between performance and the food system would indicate strategic dietary formulation and food system design. There is still a gap in food acceptability knowledge, and the current AFT research plan will include studies that investigate health, performance, and psychosocial relationships to the acceptability, variety, and design of potential long duration food systems in the next few years. It is expected that these studies will require collaborations with experts in behavioral health. Some of these studies are currently underway, simultaneously investigating relationships between food system acceptability, food intake, and psychosocial impacts with strategies to reduce mass (in collaboration with NASA Behavioral Health and the NSRDEC) (Sirmons et al. 2015) as well as the interactions with grow-pick-and-eat salad crop systems (Massa et al. 2015). It is expected that the data will suggest the appropriate food system balance generated by the cost of crew time and resource usage and effects on stress, performance, perceived food acceptability, mood, and crew unity.

Food-03: We need to identify the methods, technologies, and requirements that will deliver a food system that provides adequate safety, nutrition, and acceptability for proposed long-duration Design Reference Mission operations.

The gap Food-03 is a mitigation gap for all aspects of the food system. Processing and storage solutions simultaneously affect safety, acceptability, and nutrition. Recent work and potential solutions are reviewed below.

Food packaging significantly contributes to product shelf life. The effects of relative humidity and oxygen on dry and high lipid products varies significantly, depending on packaging and storage conditions (Catauro and Oziomek 2011b). The superior barrier properties offered by aluminum foil containing laminates aids in preventing oxidation and water activity increases that may lead to vitamin destruction, altered texture, flavor, and aroma profiles and, in the worst cases, enable the growth of microorganisms. Data suggests that, at high relative humidity (50-75%), products packaged without an aluminum layer equilibrated with the external environment and reached unacceptable levels of oxidation and increases in water activity (unpublished data, Evidence Category I) (Catauro and Oziomek 2011b). Unfortunately, the foil

layer presents several challenges that are considered under Section VII, Resource Utilization. Further research is needed to find alternatives with superior barrier qualities.

The presence of residual oxygen in the final package can cause oxidation, which leads to off-flavors. Prior to 2011, all packages were flushed with nitrogen to remove residual oxygen from packages. However, this process proved ineffective, resulting in large amounts of oxygen remaining in the final food package. An improved method of vacuum sealing, with longer flush cycles was developed to decrease the amount of oxygen entrapped in the food package (unpublished data, Evidence Category II) (Oziomek and Cooper 2010). A subsequent packaging study with Butter Cookies demonstrated that the percentage of oxygen present in the headspace of cookie packages was below 2.5% after one year of storage. Oxygen scavengers further decreased the percentage of oxygen in the headspace to 0.5% or less. No oxidation was noted in chemical analyses of the cookies. However, moisture increases were significant, particularly with the packages containing oxygen scavengers. The oxygen scavengers used a ferric system which reacts with available water to bind oxygen but unless a flux of moisture into the pouch was caused by the scavenger, this packaging change itself should not drive moisture increases in the baked goods. The evaluation of Butter Cookies also demonstrated that the initial development of off-flavors may not be the direct result of fat reacting with residual oxygen, but the rancidity and chemical activity that comes with higher moisture (Cooper et al. 2015). Additional work is needed to mitigate moisture ingress.

Inadequate oxygen barriers were noted to impact the quality of two NASA products test-processed with microwave-assisted thermal sterilization (MATS) (Cooper et al. 2015). The oxygen transmission properties of the test pouch are listed in Table 5, along with current retort package properties. Quality decrements in the food and the details of MATS and other emerging technologies are discussed in a later section of this report. Packaging that is compatible with alternative processing methods, such as MATS and Pressure Assisted Thermal Sterilization (PATs), and that retains an oxygen and moisture barrier similar to the retort pouch, is still a gap to the capability to sustain initial quality benefits obtained from emerging technologies.

Table 5. Microwave-assisted pouch barrier as compared to retort pouch barrier

<i>Package</i>	<i>Oxygen Transmission Rate (OTR) (cc /100in² · day), 21°C</i>
<i>2012 MATS pouch</i>	<i>0.0114</i>
<i>2014 MATS pouch</i>	<i>0.0276</i>
<i>Current retort pouch</i>	<i>< 0.0003</i>

Packaging improvements are only one method for mitigating an inadequate food system and increasing the quality of the food. Packaging studies along with the aforementioned shelf life findings and the NASA food nutritional degradation results indicate that in order to achieve a food system with a three to five year shelf life, additional mitigating strategies and even a combination of strategies will be required. These studies determined that nutritional content, flavor, color, and texture are affected by the high heat treatments used for processing, the residual oxygen and ingress of oxygen and moisture into food packages, and the storage conditions (temperature, relative humidity).

One potential method for ensuring adequate nutritional delivery is food fortification. Studies are ongoing to determine the long-term stability and sensory impact of commercially available vitamins on traditionally processed space foods. Five vitamins (vitamin E, vitamin K, pantothenic acid, folic acid, and thiamin) were added to four freeze-dried foods (Scrambled

Eggs, Italian Vegetables, Potatoes Au Gratin, Noodles and Chicken) and four thermostabilized foods (Curry Sauce with Vegetables, Chicken Noodle Soup, Grilled Pork Chop, Rice with Butter), such that the vitamin concentration per serving would be expected to equal 25% of the recommended daily intake (RDI) after two years of ambient storage. Additional overages were provided for the thermostabilized vitamin premix to mitigate the vitamin losses that might occur during thermal processing and accelerated thiamin degradation in higher molecular mobility environments (Bell and White 2000; Ottaway 1993). Fortificants must remain stable at levels above 85% of the original amount after two years for consideration in the spaceflight menu, as excessive doses cannot be added initially to account for losses through five years or there may be a risk of vitamin toxicity (Sirmons et al. 2016).

All vitamins, with the exception of thiamin, retained at least 85% of the originally added dose (25% of the RDI) after one year of storage at 4°C, 21°C or 35°C in six of the eight food matrices that were evaluated. Thiamin levels in all thermally processed foods fell drastically within the first six months of 35°C storage (Figure 2). No deleterious effects on sensory quality of the foods were noted after one year of storage at 4°C and 21°C. Vitamin fortification appears to be a plausible mitigation step to inadequate nutrition for long-duration space missions but additional work may be needed for different storage conditions and food matrices (Sirmons et al. 2016).

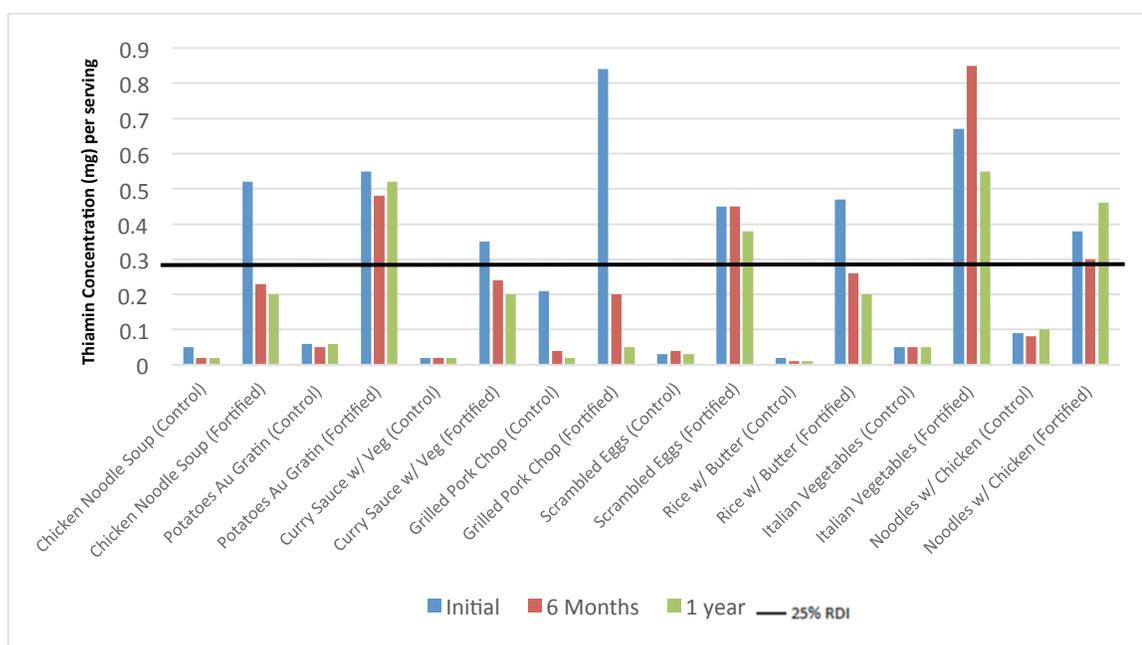


Figure 2. Concentrations of Thiamin in Fortified and Control Spaceflight foods after six months and one year of Storage at 35°C. Thiamin concentrations in all thermostabilized foods - Chicken Noodle Soup, Curry Sauce with Vegetables, Grilled Pork Chop and Rice with Butter - decreased by 56%, 31%, 76%, and 45%, respectively after six months of storage.

Increasing the number and variety of functional foods is another potential mitigation strategy to detriments in health and performance that has yet to be explored in spaceflight. Research reveals that a diet preventing bone loss should be rich in lycopene, flavonoids, omega-3 fatty acids and in fruits and vegetables (Chen et al. 2006; New 2003; O'Keefe et al. 2015; Prynne et al. 2006; Sahni et al. 2009; Weaver et al. 2012; Zwart et al. 2010). For example, some compounds from avocado exhibit positive effect on the symptoms of knee and hip osteoarthritis (Lu et al. 2009), and a diet rich in lycopene can be used as treatment against bone loss (Ardawi et

al. 2016). Nuts, while widely touted for cardiovascular benefits, also seem to reduce the development of diabetes in women and the risk of gallstone formation (Sabaté and Ang 2009). Berry fruits, laden with polyphenols and vitamin C, are linked to cardiovascular and cancer prevention benefits (Szajdek and Borowska 2008). The bioactivity of these foods is attributable to a concentration of one or more compounds, and potentially even the synergistic natural combination of thousands of phytochemicals, within the food matrix that cannot be reproduced by a supplement (Li et al. 2013; Liu 2003a; Podmore et al. 1998).

Some functional foods also have mood-enhancing effects that can be used to improve crew health and performance during long-duration space missions. For example, chocolate and thiamin have been shown to improve mood and cognitive function in adults (Macht and Dettmer 2006; Parker et al. 2006; Zhang et al. 2013). Adequate intake of some nutrients, such as omega-3 fatty acids, folic acid, and thiamin are found in large quantities in some foods with functional health attributes, and are linked to benefits such as the prevention of feelings of depression, mood disorders, and even aggression (Frasure-Smith et al. 2004; Logan 2004; Singh 2014).

To purposefully implement functional foods within the space food system, availability of the foods and the stability of both the sensory acceptability and the bioactive compounds must be determined (Cooper and Douglas 2015; Smith et al. 2016). A limited variety of foods with high-lycopene, high-lutein, or high-omega-3 fatty acid content can be delivered from the current spaceflight food system, but will likely need to increase in variety for long duration missions. The antioxidant capability of analyzed space foods - cumulatively, if not individually - is projected to be adequate and representative of a balanced diet. Stability analysis indicates that some bioactive compounds, like lycopene, lutein, marine omega-3 fatty acids, and rice sterols, will plateau at some equilibrium concentration (Cooper and Douglas 2015; Smith et al. 2016). The lutein stability in leafy vegetables and the anthocyanin stability suggests a relationship to storage conditions. The sterol stability in nuts would seem to relate to storage duration but not temperature (Cooper and Douglas 2015). More data is needed to confirm these observations. Upcoming studies will determine the effect of targeted functional food improvements in the space food system on immune, gut microbiome, and nutritional status to inform more efficient dietary interventions (Douglas et al. 2016).

The integration of optimized processes, storage environment, packaging, and products to increase food quality and nutrition and ultimately extend shelf life have begun to be investigated (Cooper et al. 2015). There are some emerging processing technologies that have demonstrated potential in providing higher quality commercially sterile products (Park et al. 2014). It is expected that these higher quality products will have extended nutritional stability. Two technologies - high pressure processing (HPP) and microwave sterilization - have the most commercial potential according to a worldwide survey of novel food processing technologies expected to have processing impact now and in 10 years (Jermann et al. 2015).

Microwave sterilization is a high-temperature, short-time process that shortens the thermal treatment to 10 minutes at 130°C (SSC-Natick 2004). The MATS process did not improve the product quality of two NASA products (Sweet and Sour Pork or Carrot Coins) such that a five-year shelf life is feasible with a processing change from retort thermostabilization alone. The MATS processing did provide better color and texture initially. However, the packaging allowed substantial oxygen ingress at higher temperatures, which was detrimental to carotene pigmentation, chlorophyll stability, and several vitamins as well as fat stability in sauces. Textural degradation proceeded after MATS processing at the same rate as textural degradation after thermostabilization. Vitamin stability was not improved by the change in

process. Since NASA testing, one package compatible with MATS has been shown to be comparable to metallized retort pouches (Zhang et al. 2015), but it has yet to be tested with complex, multicomponent foods like those in the space food system.

HPP is a nonthermal pasteurization process in which food is subjected to elevated pressures (up to 135,000 psi, which is approximately 900 MPa or 9,000 atm), to inactivate vegetative cells and enzymes. The pressure causes only small product temperature increases around 3-9°C/100 MPa (Patterson 2005). Pressure-assisted thermal sterilization (PATS) is a variation of HPP, which combines pressure with a reduced sterilization temperature to inactivate spores and produce commercially sterile products (Wimalaratne and Farid 2008). The comparison of PATS processed fruits with retorted fruits showed that PATS does circumvent much of the damage to internal cellular structure during processing, as demonstrated by higher forces required to shear PATS products. Using a combination of refrigeration and PATS processing is expected to result in organoleptically-acceptable fruit quality for most fruits through five years (Cooper et al. 2015). However, prior to adequate evaluation of nutritional and quality stability, the technology would require further development and compatible packaging would need to be identified or developed.

Low temperature storage options are currently being investigated as part of the integration approach to maintain food quality. Mass, volume, and power constraints reduce the possibility of refrigeration on the vehicle. Therefore, the possibility of storing food in the ultra-cold conditions beneath the Martian surface, protected from the planet's extreme temperature shifts, has been evaluated (Cooper et al. 2015). Thermostabilized fruits have significant quality issues when stored at ambient temperatures, but initial evaluation indicated that colder temperatures alone did not drive enough stabilization in the assessed products to reasonably achieve a five year shelf life through storage modifications. In fact, ultra-cold freezing conditions reduced fruit firmness immediately through irreversible ice damage (Cooper et al. 2015). Ice damage could likely be tempered by use of a flash freezer (Reid 1990) but such a scenario implies frozen terrestrial storage and frozen storage for the transport vehicle as well. Future integration approaches will need to investigate alternative high-barrier packaging in combination with promising new technologies, blast freezing, and reduced temperature storage in an effort to increase shelf life for long duration missions.

Current resource restrictions will likely limit initial exploration missions to prepackaged foods, but within these constraints 3D printed foods have the potential to enable personalized precise addition of nutrients to customized foods as a real-time countermeasure to nutritional inadequacies or symptoms (Sun et al. 2015; Yang et al. 2015). A prototype 3D food printer has already demonstrated capability to mix shelf stable raw ingredients and print customized foods, with future improvements expected to provide complete automation and compatibility to spaceflight habitat environments (Irvin 2013). While these concepts are in their initial stages, their development would enable supplementation of the prepackaged food system with some customized foods and nutrition on a crewmember specific basis.

The effect of space radiation on nutrition and acceptability is another concern for long duration missions. Although radiation has not been shown to reduce nutritional content in low Earth orbit (Zwart et al. 2009), the ability of galactic cosmic rays and solar flares to initiate unacceptable changes to food quality and reduce nutritional content in deep space is unknown. Galactic cosmic ray doses are expected to be at cGy levels, with solar flares adding unknown amounts over long duration missions (Hu et al. 2009; Townsend et al. 2011). This may not seem concerning considering that some foods are irradiated with gamma photons or electrons to

provide commercial sterility or decrease bacterial content. However, only some foods are selected for irradiation processing, and they are frozen prior to treatment to protect the quality and nutritional content. Additionally, foods and nutrients react differently to doses and sources of radiation. Thiamin is more unstable to gamma than to electron beam irradiation (WHO 1999). Studies with soybeans have demonstrated that doses as low as 1 Gy can lead to oxidized flavors and reduce production yields (Wilson et al. 2007b). The effect that particulate radiation present in galactic cosmic rays and solar particle events will have on food is unknown (Hu et al. 2009), and must be quantified to ensure development of a nutritious and acceptable food system.

Further research and innovative technologies might ensure adequate nutrition for long duration missions. However, the ability to deliver this nutrition during contingency operations requiring a pressurized spacesuit in a hypobaric, microgravity environment is currently not possible. The importance of effective in-suit nutrition delivery in an emergency event, such as depressurization of the crew vehicle, becomes critical depending on the length of the event. No commercial product has been identified that meets all spaceflight requirements. In fact, some options would supply toxic levels of several nutrients if enough of the product were provided to be the only source of nutrition.

A prototype fluid delivery system that would overcome the pressure differential, and the guidelines for a nutritional beverage compatible with the delivery system were established for a contingency cabin depressurization event, in which crewmembers would be in a pressurized suit for up to 144 hours. A bag-in-bag (BiB) prototype, designed to equalize the suit pressure with the beverage pouch and enable a crewmember to drink normally, was operated successfully in both vacuum chamber and suited subject tests. A Boa restrainer pouch, designed to provide mechanical leverage to overcome the pressure differential, was not successful, and recommendations for improved performance have been offered. Guidelines for developing contingency beverage prototypes, including viscosity and rehydration properties, were compiled based on their compatibility with the delivery hardware. Contingency beverage shelf life predictions were calculated based on generated vapor sorption isotherm curves (Glass and Leong 2014). Further refinement of the dispensing system and additional iterations of a nutritional, acceptable liquid product are critical to prevent malnutrition during suited contingency operations.

VII. Resource Utilization

A. Spaceflight Food System Resource Utilization Background

During the development of a space flight food system, several resources have to be considered including mass, volume, power, crew time, water use, and waste disposal capacity. Ineffective use of vehicle resources will decrease the possibility of mission success. Resource constraints on each space vehicle drove several food system requirements and modifications as mission lengths increased. The lack of refrigeration required foods to be shelf stable. The production of byproduct water from fuel cells on the Shuttle drove the development of freeze-dried foods, reducing initial launch mass and volume. The hard plastic spoon bowls designed for freeze-dried and low moisture foods during the Apollo era were reduced to a clear, flexible plastic laminate. Instead of rigid cans, a flexible laminate with an aluminum foil layer was used for thermostabilized foods. The flexibility of these packages reduced mass and volume requirements during stowage (Perchonok and Bourland 2002).

Food packaging is a major contributor to mass, volume, and waste allocations for NASA missions. Packaging is integral to maintaining the safety, nutritional adequacy, and acceptability of food, while protecting it from foreign material, microorganisms, oxygen, light, moisture, and other modes of degradation. High packaging barrier properties equate to greater protection from oxygen and water ingress. Oxygen ingress can result in oxidation of the food and loss of quality or nutrition. Water ingress can result in quality changes such as difficulty in rehydrating the freeze-dried foods and increased enzymatic and microbiological activity.

Currently, a clear, flexible, plastic laminate is used for freeze-dried and natural form foods, enabling visual product inspection. Additionally, the clear plastic is able to be thermoformed and thermosealed without flex cracks that are common with foil laminates. However, the clear packaging does not have adequate oxygen and moisture barrier properties to provide an 18-month shelf life for ISS. As a result, foods are overwrapped with a second opaque foil-containing package that has higher barrier properties. The packaging materials used for the thermostabilized, irradiated, and beverage items contain a foil layer that protects the food from oxygen and moisture beyond the required 18-month shelf life. Tables 6 and 7 list the oxygen and water vapor permeability of the current NASA food packaging materials.

Table 6. Oxygen Permeability of Packaging Materials (cc/100 in²/Day)

Food Product Use	73.4°F@100% Relative Humidity
Overwrap Pouch (used with rehydratables and natural form food)	0.0065
Thermostabilized and Irradiated Pouch	<0.0003
Rehydratable Primary Pouch Lid and Natural Form Primary Pouch	5.405
Rehydratable Primary Pouch Base (thermoformed*)	0.053

*heating and molding a thermoplastic material

Table 7. Water Vapor Permeability of Packaging Materials (g/100 in²/Day)

Food Product Use	100°F@100% Relative Humidity
Overwrap Pouch (used with rehydratables and natural form food)	<0.0003
Thermostabilized and Irradiated Pouch	0.0004
Rehydratable Primary Pouch Lid and Natural Form Primary Pouch	0.352
Rehydratable Primary Pouch Base (thermoformed*)	0.1784

*heating and molding a thermoplastic material

B. Resource Use During Spaceflight

A significant resource concern lies with the mass of the food system. The mass of the food is dependent on the type of food and the quantity required per crewmember. The Apollo 7 food system provided 0.82 kg of food per person per day (Smith et al. 1975). Starting in 1968, thermostabilized foods were included in the food system and were preferred to freeze-dried

options, justifying the weight increase. By Apollo 14, the mass of the food averaged 1.1 kg per person per day (Smith et al. 1975). The Apollo food system still contained a significant number of freeze-dried foods since water from the fuel cells was available for food rehydration (Evidence Category III).

Current ISS crewmembers receive about 1.83 kg of food plus packaging per person per day. Compared to the Apollo missions a higher percentage of the food is now thermostabilized, which supports crew preference, but increases the total weight of the food system. Furthermore, the average number of calories is now based on the actual caloric needs of each crewmember according to activity, body weight, and height. This results in an average caloric requirement of 3,000 kcal as opposed to the 2,500 kcal provided to the Apollo crews, and a corresponding food weight increase (Evidence Category III). ISS uses solar panels for a power source, and not fuel cells that produce water as a by-product, so until recently there was little mass advantage to using freeze-dried foods. Now the majority of the water supply on ISS is recycled, but the proportion of retort thermostabilized foods to freeze dried foods has been maintained to ensure adequate food variety, acceptability, and intake to support crew health.

Food packaging produces a significant amount of waste. In confidential crew debriefs, NASA crewmembers have stated that the overwrapped foods create a trash management problem, since there were two food packages per food item for the rehydratables and natural form foods. Even though the foods were not overwrapped on Shuttle missions, the trash was still significant. Around 60% of the waste mass on STS-99 was generated from the food system (including food, drinks, and packaging). The food system generated 86% of the waste mass on STS-101 (Lee 2000). An analysis of the food waste on STS-51D showed a total trash mass of 23 kg that included 12.2 kg of uneaten food and 10.8 kg of food packaging. Eighty-five percent of the trash by volume on STS-29 and STS-30 was food packaging and 7% was food (Wydeven and Golub 1991). (Evidence Category III).

C. Constraining Food System Resource Use in Context of Exploration Missions

The provisioning of a safe, nutritious, and acceptable food system must be balanced with available resources on each specific mission. For one or two day missions between Earth and ISS, mission planners may compromise food acceptability to accommodate the small vehicle volume, eliminating hot water and a food warmer. While the decrease in food acceptability may be tolerated for short two-day missions, the balance between resources and food will need to be reassessed with each increase in mission length to prevent inadequate caloric intake and nutritional deficiency. Food allocations are estimated to be one of the primary drivers of total logistics mass for crew consumables, given the direct scaling with both crew size and mission duration. Food mass constituted 52% and 66% of the total dry consumables mass estimates for the cis-lunar and Mars missions respectively (Lopez et al. 2015). Food packages may be reused as one of the major components of trash bricks, a proposed method of radiation shielding that also reduces overall required mass for habitat structures (Broyan et al. 2014). Other allocations for the food packages are also being considered.

There is a risk that the food system mass and volume will be too constraining as mission lengths extend to three to five years. In the event of a bioregenerative system, there is a risk that acceptable food may not grow as expected due to radiation, reduced gravity, or different atmospheric pressures. Infrastructure required to grow crops extraterrestrially will increase mass and volume constraints (Perchonok et al. 2011). There is the potential risk of equipment not

working or water quantities being inadequate for food hydration, processing, or preparation. There is also the risk that the bioregenerative food system could require too much crew time. Such resource constraints on the system could delay a Mars mission even if all other elements of the mission were ready. The risks increase with the increased length of the Mars mission, longer term effects of radiation, especially during transit, and the lack of resupply during the mission.

D. Evidence of Constraining Food System Resource Use for Exploration Missions – Ground and Spaceflight Research

Any solutions to mass reduction must also ensure maintenance of safety, nutrition, and acceptability. Therefore, all mass reduction work falls under the mitigation gap, Food-03.

Recent research has demonstrated that the mass of the current food system can be reduced by taking advantage of new packaging techniques and adjusting product formulations (unpublished data, Evidence Category IV) (Catauro and Perchonok 2012). However, even without packaging it is estimated that the mass of food required to be launched for six crewmembers on a three year mission will be nearly 11,000 kg. Based on this constraining resource use, and the inadequate nutrition and acceptability of the current prepackaged food system, mass reduction options and alternative food systems for long duration missions must be considered.

Packaging is about 15-17% of the mass of the total food system. The bulk overwrap currently used to protect freeze-dried and low moisture foods from oxygen and moisture is a significant contributor to food system mass and waste. It was determined that around 3% of prepackaged foods would be left in the package if an attempt was made to eat everything (Duffield 2008). It would therefore be expected that, at a minimum, 18% of the rehydrated food system would become waste (Levri et al. 2001a). (Evidence Category I)

Recently, packaging evaluations enabled replacement of rigid collapsible food containers with flexible, large overwraps on the International Space Station, saving around 15-17% in upmass (unpublished data, Evidence Category II) (Catauro and Oziomek 2011a). Another path to reduce packaging waste could be the use of an alternative packaging material. Alternative packaging would ideally provide moisture and oxygen protection similar to the current packaging without a foil layer. While the current foil packaging provides an excellent barrier, the tendency for flex cracks limit its use with thermoforming equipment currently used to heat and mold the shape of the rehydratable food packaging, and it is not compatible with some emerging technologies that may be used to produce higher quality commercially sterile foods. In addition, foil packaging complicates plans to incinerate trash at an extraterrestrial base, as it will not incinerate completely and will leave some ash (Wydeven and Golub 1991). Food system wet waste materials must be properly disposed of to limit microbial contamination to the crew.

Previous work compared the effectiveness of a flexible aluminum-oxide coated laminate (Tolas®) against the current primary clear laminate (Combitherm®) and a material more similar to the current aluminum foil and plastic laminate overwrap (Technipaq®). Analysis of barrier properties indicated that the Combitherm® material does not provide a sufficient barrier and requires overwrap. However, evaluation of alternate materials has not yet resulted in identification of a material that would maintain adequate barriers independent of a secondary aluminum overwrap (unpublished data, Evidence Category I) (Catauro and Oziomek 2011b).

The identification of a capable packaging material lends itself to other packaging reductions. A gusseted pouch design for rehydratable foods would be easier to produce and would minimize mass, volume, and waste compared to the current thermoformed rehydratable package (unpublished data, Evidence Category II) (Oziomek and Cooper 2010). The gusseted pouch reduces the production process from three pieces of packaging equipment to one. Without a requirement for thermoforming, aluminum packaging could potentially be used to reduce the packaging from two pouches to one, decreasing the total amount of packaging mass by approximately 66%.

Significant reductions in food system mass are also possible with further menu development. Results of an examination of the nutrient and caloric densities of the current space food are shown in Figure 3. Naturally Nutrient Rich (NNR) scores were calculated as the average of the percentage daily values (DVs) for 16 nutrients given 2000 kcal, or 8368 kJ, of each particular food item(Drewnowski 2005):

$$NNR = \frac{\sum \%DV_{2000\text{ kcal}}}{16} \quad (1)$$

The 16 nutrients, with selection revised for space application, were protein, calcium, iron, vitamin A, vitamin C, thiamin, riboflavin, vitamin B₁₂, folate, vitamin D, vitamin E, magnesium, potassium, zinc, fiber, and pantothenic acid. In this analysis, the energy-dilute foods, such as beverages and vegetables, have the highest NNR score for the evaluated nutrients. Substantially more beverage and vegetable mass would be required to achieve required caloric delivery if these categories were heavily proportioned to provision the crew. In contrast, nuts are the most efficient offering currently, having relatively high energy and significant nutrients in a compact food matrix. Directional shifts of the food supply to the upper left portion of Figure 3 would ultimately allow a smaller mass of food to meet the required macronutrient and micronutrient needs of the crew(Cooper 2016).

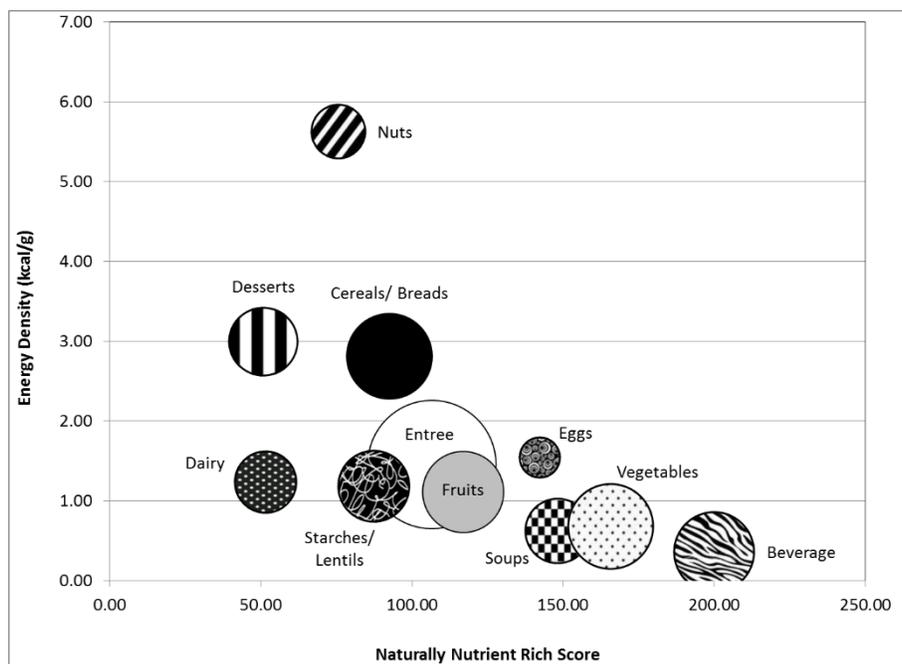


Figure 3. Caloric and nutrient density of current ISS space food system(Cooper 2016)

It has been projected that overall calories could be maintained if the caloric density of menu items were increased by adding more fat and reducing moisture. The increase in caloric density would reduce system mass by 321 g per crew member per day, or 22% (unpublished data) (Stoklosa 2009). In another estimation, the substitution of standard menu items with meal replacement bars at a frequency of one bar per crew member per day would result in a mass reduction of 240 g, or 17% (Stoklosa 2009). If both approaches were combined, it is estimated that the mass of the food system can be reduced by as much as 529 g, or 36% (Evidence Category I).

Resource constraints on near term Orion missions are driving a requirement for a 10% reduction in food system mass. These initial exploration missions will not have water recycling or production capabilities so moisture reduction in the food would only increase the water upmass requirement and would not result in a mass savings. Therefore, nutritionally dense meal replacement bars that meet the nutritional, safety, and acceptability requirements for spaceflight are under assessment as a mass reduction strategy. Five nutrient-dense meal replacement bars have been developed in collaboration with NSRDEC, using both traditional and ultrasonic modes of compression. The developed bar varieties include both sweet cake-like bars (Banana Nut, Ginger Vanilla, Orange Cranberry) and savory nutty bars (Jalapeno Nut and Hickory Smoked BBQ Nut) and contain a combination of soy and whey proteins, which are intended to increase bar satiety (Hall 2003). The initial bar acceptability ranged from 6.5 – 7.45 on the 9-point Hedonic scale. On average, the bars provide approximately 700 kcal per serving and have an estimated caloric density of 4.10 kcal/g. Daily bar substitution with the current breakfast menu enables a mass savings of approximately 10% across the food system (Evidence Category I). It is not yet known if early quality changes in the bars will impact long-term shelf life, whether micronutrient fortification will be sustained in the bars, or at what maximum frequency the bars can be used in the food system without impacting food intake and crew psychosocial health. These factors are currently being evaluated in ground-based analog and shelf life studies prior to menu incorporation and final assessment of mass savings (Sirmons et al. 2015).

Hydroponically grown produce is another viable path for reducing initial food system mass and adding variety to the menu. The first introduction of produce into the food system will likely be a small garden operation, with salad crops that will be consumed raw, providing an inconsequential amount of calories but offering a psychological benefit and sensory variety. Initial testing of vegetable varieties suitable for growth in the conditions of the Veggie plant growth chamber on ISS have included lettuce, dwarf tomato, and dwarf pepper plants (Wheeler et al. 2016). Crops were evaluated and prioritized in ground based studies based on edible mass, growth rates, specific nutrients including potassium and vitamin K, and sensory acceptability. Future work on leafy greens and dwarf tomato crops is planned to evaluate light and fertilizer treatments to optimize growth conditions in the Veggie chamber on ISS (Massa et al. 2015). It is expected that these initial “grow-pick-and-eat” studies will lead to more extensive bioregenerative food systems as hardware concepts and infrastructure requirements are proven, growth parameters are optimized, production is consistent and dependable, and resource and crew time requirements are minimized.

Implementation of bioregenerative foods introduces a risk of foodborne illness from contaminated produce. While on Earth produce may be washed with food grade sanitizers or processed, in microgravity the ideal disinfection technology should be waterless, require minimal resources, produce minimal waste, be safe for crew members, and effectively reduce microbial loads. Cold plasma is a developing technology based on highly reactive species such as

nanoparticles, ions, free radicals, electrons, and electromagnetic radiation such as UV light. Microbial inactivation is achieved through oxidation processes, erosion and perforation of cells, DNA-damage and other secondary effects. Cold plasma has been used to inactivate microorganisms on the surface of a variety of food products, including fresh produce. This technology has also been used to extend the shelf life of a number of packaged products, such as strawberries (Misra et al. 2014a). Studies have demonstrated that the technology is effective against some of the most common foodborne pathogens, including *E. coli*, *Salmonella* spp. and *Listeria monocytogenes*. Other microorganisms such as *Aspergillus* and *Penicillium* sp. and a number of spoilage microorganism are also sensitive to cold plasma (Misra et al. 2011). Recently, a system was developed to utilize nonthermal, atmospheric pressure plasma to disinfect produce grown in spaceflight (Remiker 2012). The atmospheric pressure plasma technology was shown to be effective against *Salmonella* spp. and *Escherichia coli* on three fresh vegetables (tomatoes, lettuce and radishes). Treatments of 15 minutes with lab air resulted in up to a 3.7 log-reduction of *E. coli* on tomatoes and lettuce. No notable quality changes were detected in the vegetables after processing, indicating that the technology can preserve the fresh-like appearance of treated produce. Other studies have also shown that treatment with cold plasma does not impart off odors, color or flavors in the final product, nor destroy the nutritional content of treated vegetables (Lacombe et al. 2015; Misra et al. 2014b). Further evaluation of cold plasma technology will determine its potential for spaceflight use to ensure the safety of pick-and-eat vegetables.

Earth-based studies have been conducted to determine the requirements of a more complete bioregenerative food system for an extraterrestrial mission, with an attempt to balance mass, volume, crew time, and power requirements with nutrition and acceptability. In one trade study five menus were evaluated (Table 8) using Equivalent System Mass (ESM) (Levri et al. 2001a). ESM converts mass, volume, power, cooling, and sometimes crew time requirements, into one mass value. The volume, power, cooling, and crew time requirements are converted to mass using equivalency factors. These equivalency factors are based on mission length and location.

Table 8. Food System Options (Levri et al. 2001a)

Case	Food System	Packaging Approach	Crop Growth
1	ISS Assembly Complete (some frozen food)	Individual Servings	Salad
2	Shuttle Training Menu	Individual & Multiple Servings	Salad
3	Shuttle Training Menu	Individual Servings	Salad & White Potato
4	Shuttle Training Menu	Individual Servings	Salad
5	Shuttle Training Menu w/reduced water content	Individual Servings	Salad

The Shuttle Training menu was similar to the Shuttle and ISS food system. The various cases supplemented the Shuttle Training menu with frozen foods, bulk packaged snack foods and/or salad and/or potatoes. The salad and potatoes would be grown on the Mars surface. If only ESM was considered in choosing a menu, either case 2, case 4, or case 5 would have been chosen (Table 9). However, non-quantifiable aspects (with respect to ESM), such as food palatability and psychological benefits of plant-crew interaction were not able to be

included and would need to be considered when evaluating food systems (Levri et al. 2001a) (Evidence Category I).

Table 9. Non-crew time ESM, Crew time ESM and Total ESM (Levri et al. 2001b)

ESM	1 (frozen)	2 (multiple serving)	3 (potato)	4 (indiv)	5 (reduced water content)
ESM _{NCT} *	27,587	23,246	27,198	23,324	23,351
ESM _{CT} **	4,398	3,635	4,848	3,650	3,654
ESM _{TOTAL}	31,984	26,881	32,047	26,974	27,005

* non-crew time; ** crew time

During the Lunar Mars Life Support Test Project simulation, a four-person crew tested a 10-day vegetarian diet based on crops expected to be grown during long duration missions. The crops were processed into ready-to-use ingredients outside of the chamber, leaving general cooking activities and cleanup to the crew. The general preparation and cleaning activities required 4.6 crew hours total per day. The amount of waste, mostly from leftovers, ranged between 20-80%. This experience demonstrated a need for automated processes, a diverse menu, and improvements in recipe scaling based on crew size (Kloeris et al. 1998) (Evidence Category II).

Preliminary studies determined that food preparation would require about three active hours and six passive hours of crew time per day for a crew of six (unpublished data, Evidence Category II) (Perchonok 2006). Passive time was defined as the preparation time that did not require a crewmember to constantly watch over the process, such as baking. Currently, only 30 minutes is set aside for crew to prepare a meal on ISS missions.

Additional limitations and benefits of a bioregenerative system were determined, compared to a prepackaged system for a three year mission, where resupply is defined as ingredients that are either prepositioned or shipped with the crew at the start of the mission (Cooper et al. 2012). The study evaluated five food systems for a crew of six, with each scenario incorporating different levels of a bioregenerative system (Table 10). Fresh fruits and vegetables (farm edible), such as spinach, lettuce, tomatoes, carrots, bell peppers, onions, potatoes, and strawberries could be grown hydroponically in environmentally-controlled chambers. In addition, baseline crops such as wheat, rice, peanuts, and dried beans could be grown on the surface or launched in bulk from Earth. These crops would be processed into edible ingredients and used in preparing meals in a galley. Mass assumptions for each food system do not include packaging due to continuing packaging development that will likely change mass numbers over time.

Table 10. Food and equipment mass for five different food system scenarios. Shipping masses include small scale processing equipment when required (unpublished data).

Food System		Edible Crop (kg)	Ship (kg)
1	Farm edible, grow wheat/rice/beans/peanuts	12058.2	2041.3
2	Farm edible, ship wheat flour/rice/beans/peanut oil	7651.3	4854.4
3	Farm with prepackaged food and resupply	9650.5	3103.0
4	Farm, bulk, prepackaged, and resupply	6266.0	5271.5
5	Prepackaged food only	0	10765

While food items prepared from ingredients included in the bioregenerative system received an average acceptance score of a 7.45 on a 9.0 Hedonic scale, almost two hours of active crew time is required per meal (unpublished data, Evidence Category II) (Cooper and Catauro 2013). The crew time and mass requirements are constraining the available resources on long duration missions. Additionally, dependence on the processing and preparation of bioregenerative and bulk commodity foods presents unique risks for these missions, including the risk of food scarcity from failed crop production.

Providing ease of use (preparation difficulty and time) and a constant supply of food with respect to crew scheduling will be necessary to prevent inadequate caloric intake and associated nutritional and psychological issues. Excess food preparation time also impacts the time available for scientific and maintenance endeavors (Evidence Category III). However, current studies are determining the benefits that a fresh food system and the food preparation experience will provide the crew on long duration missions. Aspects of a bioregenerative system may provide enough benefit to balance out crew time and mass costs when crewmembers must live and work in an extreme extraterrestrial environment for several years. A food metric value assessment will enable inclusion of factors such as nutrition, palatability, variety, and psychological benefit in the ESM comparison to ensure provisioning of an adequate food system for long duration missions (Cooper and Catauro 2013; Cruthirds et al. 2002). Metric assessments are expected to feed into a final gap, Food-04.

Food-04: We need to identify tools or methods that can be used or developed to help mission planners and vehicle developers determine the most effective combination of methods, technologies, and requirements to balance crew food system needs with vehicle resources.

This gap will integrate all possible food system options and limits into a “trade space” to enable mission planners to determine the appropriate balance of systems based on DRM and vehicle resources. It is expected that food system mitigation strategies will produce data over the next few years that can be utilized in this trade space. The trade space program is expected to process data and provide mission planners with the risks and benefits of implementing different food system scenarios to food nutrition, acceptability, and safety, and potential outcomes to crew health, performance, and psychology. It is expected that work will begin in this gap in 2019.

VIII. Conclusion

The current space food system is inadequate for long duration missions beyond low Earth orbit. Without extensive research and development to increase the adequacy of the food system, the crew’s health and performance will be compromised during these missions. It is clear that in developing future NASA food systems, a balance must be maintained between use of resources (such as power, mass and crew time), and the safety, nutrition and acceptability of the food system. Nutrition, acceptability, and resource utilization may take on different priorities based on mission duration and distance from earth. Incorporation of fresh foods, and/or food processing and food preparation during long-duration missions may increase the probability of safety and resource utilization issues, but may provide a psychosocial boost and decrease the possibility of inadequate nutrition and acceptability issues.

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X. Team

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XI. List of Acronyms

AFT	Advanced Food Technology
ESM	Equivalent System Mass
GMP	Good Manufacturing Practice
HACCP	Hazard Analysis Critical Control Point
HPP	High Pressure Processing
HRP	Human Research Program
ISS	International Space Station
JSC	Johnson Space Center
PATS	Pressure Assisted Thermal Sterilization
SHFH	Space Human Factors and Habitability